# EVIDENCE FOR STELLAR CHROMOSPHERES PRESENTED BY GROUND-BASED SPECTRA OF THE SUN AND STARS

**Francoise Praderie**
*Institut D'Astrophysique, Paris*

## INTRODUCTION

## NEED FOR A DEFINITION OF A CHROMOSPHERE

Before starting to survey recent observations related to stellar chromospheres, an operational definition of a chromosphere is needed; such definition must satisfy two requirements: (1) it must be bound to a set of *observables* which we agree indicate the presence of a chromosphere; (2) it must be reasonable in terms of the *physical effects* which we say characterize a chromosphere. Indeed one does not want to be *a priori* confined to call chromospheric indicators only those spectral features which, in the Sun, have been attributed to the chromospheric regions of formation of the spectrum, and which, by analogy, can be said to be a sign of a chromosphere in stars similar enough to the Sun.

The superiority of the Sun lies in the fact that a correspondence has been established between chromospheric observables and the chromosphere as a physically defined layer of the atmosphere; a combination of both very detailed observations and a refined theory of spectrum line formation have made this correspondence meaningful. Consequently, a safe way to proceed, at the moment, would be to study stellar chromospheres as examples of solar type stars. This approach, although good if the aim is to give a quantitative description of solar-like stellar chromospheres, excludes many stars with "anomalous" spectral features; those features do not necessarily have a counterpart in the Sun's chromospheric spectrum, but nevertheless suggest that the stars showing them have an energy supply due not exclusively to radiation in their outermost layers. For the latter stars, our diagnostic tools are still poor, and this will prevent us from giving any but qualitative descriptions of their chromospheres. While we must here look at the Sun as a typical example, about which we know more because of better observations, and which will therefore serve as a guide, we will try to classify (but not to interpret in full generality) observed features pertaining to stellar chromospheres in the definition of a chromosphere based on energetic considerations.

## LIMITS OF AN EMPIRICAL DEFINITION

The preceding section implies that we already have in mind a representation of what the solar chromosphere is, both in terms of observables and in terms of physical effects. Concerning the observables, we know empirically what is the chromospheric spectrum of the Sun as observed at eclipses, and what are classically called the solar chromospheric layers, i.e. those extending from $\tau_{tang}$ (5000 A) = 1 to $\tau_{tang}$ (H$\alpha$) = 1. Further out, in the Sun, lies the corona. But clearly we have said nothing regarding the physical effects which define a chromosphere by locating it in terms of tangential optical depths. Moreover this last variable is not accessible in the majority of stars (except in eclipsing systems, e.g., $\zeta$ Aur). As a matter of fact, when starting to interpret empirical features in the solar chromospheric spectrum like emission gradients, or intensity reversals in H and K lines, one recognizes primarily that not optical depth but electronic temperature $T_e$ is the basic physical quantity which contrasts a chromosphere relative to a radiative equilibrium (RE) atmosphere; $T_e$ describes the energy balance and its departures from the pure RE case.

What we ideally want then is to give a unified definition of a stellar (including solar) chromosphere, thereby avoiding a purely empirical one, and relating it to the physical effects controlling $T_e$. From this standpoint, the atmospheric regions above the photosphere are combined, and in the following discussion there will be no need to separate chromosphere from corona. Only the problem of the base of the chromosphere will be treated, not that of its top.

## TENTATIVE DEFINITION OF A CHROMOSPHERE

We suggest that the chromosphere is the region of the star giving rise to *observables* depending upon the existence of a) a mass flux, b) a non-radiative energy dissipation. Two questions immediately arise: first, why link the existence of a chromosphere to both phenomena a) and b) and not simply to b) and, second, what kind of observables are indeed chromospheric indicators? We now turn to consider the necessary and sufficient conditions for a chromosphere.

In a star, considered as a non-equilibrium system, motions are produced in the subphotospheric or in the photospheric regions from the electromagnetic energy flux, through various instabilities. In the contracting envelope of a protostar, mass falls toward the center of the cloud. In both cases, any motion of a mass m, directed or non-isotropically turbulent, generates a mass flux which, per unit surface at time t and location z along the radius, is

$$\vec{F}_m\ (z,t) = m \int_V \vec{v}\ f\ (\vec{v},z,t)\ d^3\vec{v}$$

where $f(\vec{v},z,\ t\ )$ is the distribution function of velocities $\vec{v}$. The existence of such a mass flux does not mean that the star is, at each z, in hydrodynamical flow: This may be the case (expansion, mass inflow, mass *loss*) but other situations exist where the mean value of $\vec{F}_m$ is zero over t (e.g. acoustic waves), or over some characteristic length (e.g. convective motions). The mass flux is accompanied by a mechanical energy flux

$$\vec{F}_{me}\ (z,t) = m \int_V v^2\ \vec{v}\ f(\vec{v}, z, t)\ d^3\vec{v}$$

Hence a mass flux over a certain depth range $\{z\}$ in the atmosphere is a necessary condition to have a non-radiative energy transport (We will not consider magnetic energy here.).

But a mass flux is by no means a sufficient condition of existence for a chromosphere. Mass flux can indeed be present in the photosphere, and, strictly speaking, it implies departures from radiative equilibrium and from hydrostatic equilibrium there. But in the photosphere, there is, by definition, no dissipation of mechanical energy. By contrast, in the chromosphere, as soon as characteristic particle velocities become some fraction of the sound velocity, the energy contained in macroscopic motions is converted into microscopic, thermal ones and heating starts. Then, physically, the base of the chromosphere (or of the chromosphere-corona) is the lowest place where this dissipation starts to be effective.

The observables which point out a chromosphere are either direct indicators or indirect ones. *Direct* indicators are spectral features whose origin is in the chromosphere itself; they directly imply a chromosphere, provided a theoretical analysis allows one to attribute them to such a region. As an example, a line core presenting an emission may imply a source function that does not decrease monotonically outwards. It can be a sign of $T_e$ increasing outwards in the atmosphere (cf. Jefferies's talk). In such a case, a correspondence is established between the observable and the location where $T_e$ rises, identified with the chromosphere, if moreover, this rise in $T_e$ is not produced under RE.

Not all direct indicators of chromospheres have been analyzed in full detail; some of those which have not been analyzed are nonetheless said to be heating indicators, although only on analogical grounds at the moment.

*Indirect* indicators are phenomena observed in the photosphere *or* in the chromosphere, from which one can predict the presence of a chromosphere, without those indirect indicators necessarily being found jointly with direct observed effects. They include all signs of the presence of non-radiative energy sources. Interpretation of these signs leads not to a local $T_e$, but to the recognition of the presence of mechanical energy, which might dissipate higher up in the atmosphere, or at the location where the sign is formed.

In the case which we will exclusively consider in the following, namely, production of chromspheres from dissipation of mechanical energy, such indirect indicators directly reveal the existence of a mass flux in the star. Examples are oscillatory motions in the solar low chromosphere, astronomical turbulence, solar granulation, etc. . . .

## THE BOTTOM OF THE CHROMOSPHERE

The organizers of this conference asked for a discussion on the most valid criterium to decide where the chromosphere indeed begins. Are we in the chromosphere as soon as the temperature gradient $dT_e/dh$, derived from observations, is positive? Have we enough tools of analysis to non-equivocally attribute a positive $dT_e/dh$ to a pure RE effect or to a dissipation of mechanical energy, or to both? Let us consider different possible situations and their meanings. A first case is that in which $dT_e/dh < 0$, or $T_e$ is decreasing outwards monotonically. This case is met when there is either pure radiative or radiative plus convective energy transport, and when inelastic collisions maintain populations of energy levels.

When, in a continuum j, photoionizations take over from collisions, the effect first shown by Cayrel (1963) to act in the solar $H^-$ continuum produces an increase of $T_e$ under RE. If we ignore the lines, $T_e$ may increase up to some colour temperature $T_c$, characteristic of the most transparent continuum. Each continuum successively contributes to the increase in $T_e$ (see Feautrier, 1968; Auer and Mihalas, 1969, 1970; Mihalas and Auer, 1970; Gebbie and Thomas, 1971). The location of the layer where $T_e$ starts to rise is both frequency dependent, because the rate of photoionization in each continuum $\mathcal{R}_{jc}$ is, frequency dependent and density dependent through the rate of collisional ionization $\Gamma_{jc}$. This dependence evolves from star to star along the spectral sequence with the nature of the main absorber in the transparent layers of the star ($H^-$ in the Sun and F, G, and K stars; HI in hotter stars; HeI?) and with the gravity, which, combined with $T_e$, governs the electron density in the star.

But, as radiation is not carried exclusively in the continuum, lines enter to modify the preceding conclusions. To be brief, let us mention the work by Frisch (1966), and Athay (1970), who conclude that the lines they have considered (lines not coupled to the continuum) act as cooling agents in the Sun.

In consequence, even if $dT_e/dh$ is inferred to be negative from observations, in a region where one can show that the density is low enough that $\Gamma_{jc} \ll \mathcal{R}_{jc}$ but where the effect of lines is mainly to cool, we are in a practical situation in which we are not able to recognize the starting layer of the Cayrel effect. Suppose now that observations lead to $dT_e/dh = 0$. It may mean that the Cayrel effect is present but exactly balanced by cooling due to lines; or that we have the same, plus a strong cooling due to lines, but with a contribution of heating by mechanical dissipation. If properly analyzed observations lead to $dT_e/dh > 0$, either one has one of the former situations, with continuum influence, plus some lines coupling to the continuum to produce a heating effect stronger than the cooling due to other lines; or the same plus mechanical heating; or mechanical heating alone, if, for instance, $T_e$ is higher than the colour temperature $T_c$ of the most transparent continuum.

My conclusion is that it is impossible, at present, to decide unambiguously what is the proper interpretation of a $dT_e/dh$ inferred from observations in the low density layers of a stellar atmosphere, without having carefully studied which are the opacity sources and how lines interact with them in governing the temperature run, as well as the mechanical energy sources and where their energy is dissipated. Despite valuable efforts on this purely theoretical problem, a considerable amount of work is still needed to unravel the non-LTE photosphere from the chromospheric regions.

But the Cayrel effect in no case can increase $T_e$ over $T_c$. If, then, through appropriate observables, one diagnoses a temperature higher than $T_e$, one can claim, without the detailed analysis of all the above mentioned physical processes, that mechanical heating operates and that one sees the chromosphere. However, at present, direct indicators of a chromosphere cannot by themselves lead to the location of the base of the chromosphere, not even in the Sun.

Considering that in the Sun the question of the bottom of the chromosphere is not settled, and that the best semiempirical models have been obtained from eclipse data and from high resolution disk spectra in the core of strong lines and in UV and IR continua, we will not be able, in stars, both from lack of theoretical analysis and from the lesser quality of observations, to fulfill the program announced to be ideal in this introduction. Only a survey of observables and an attempt to classify them are possible, and we will make such a survey in the following paragraphs.

## SURVEY OF RECENT OBSERVATIONS

Two review papers on observations of stellar chromospheres were presented in 1969 (Feast, Praderie). We will attempt here to gather the recent observations and some of those which were omitted in the previous reviews and will examine successively indicators of mechanical energy dissipation, some selected indicators of mass flux, and after the Sun's example, indicators of horizontal inhomogeneities and of temporal variations in chromospheres. The present survey is restricted to observations in the visible and in the infrared.

## INDICATORS OF HEATING

These indicators are mainly line profiles showing excitation-ionization anomalies; UV and IR continua have already been mentioned (Praderie, 1970). The identification of lines as chromospheric indicators proceeds from the theoretical understanding of their formation. The most famous example is that of the solar H and K central reversals (Jefferies and Thomas, 1959). As recalled by Jefferies during this conference, all the so-called collision dominated lines are, in the same way, model dependent and may reflect chromospheric values of $T_e$ and $N_e$. Emission in some other lines is not as well understood, as the following examples will show.

Excitation anomalies include, first, the extreme case of all lines in emission (examples: Wolf-Rayet stars spectrum, or the solar spectrum below 1800 Å); second, the case where some lines are in emission (examples: He II λ4686 in Of stars, MgII and CaII resonance doublets in the Sun and many late type stars); third, the case where absorption lines appear which correspond to an excitation much higher than that existing in the photosphere (examples: He I λ5876 or λ10830 lines in cool stars).

Ionization anomalies include the presence of lines of highly ionized atoms (coronal lines) and (or) of a continuum emission in the radio wavelengths, emission whose origin is probably in a hot corona.

## EXCITATION ANOMALIES

### H AND K LINES OF CA II

Observations of the central emission in the resonance doublet of Ca II, which were extensively made by Wilson and Wilson et al (1954, 1957, 1962, 1963, 1964, 1966, 1968) and others, have been pursued actively, not so much to study individual atmospheres, as to take advantage of the presence of this feature to derive other stellar properties to which the emission is correlated. These correlations may lead to a better understanding of the sources of heating of the chromospheres as functions of spectral type (Skumanich, 1972). We first consider here time-independent observations:

- Dependence of H and K emission with bolometric luminosity (Wilson, 1970 – For 65 stars of the same age (F 4 to K 5, main sequence Hyades stars) the mean flux ratio for the emission components of H and K increases from B – V = 0.45 to B – V = 1.25, and the emission intensity to bolometric luminosity ratio increases by a factor of 2 in the same spectral type range. It is not known if this trend is universal, or if it is age dependent.

- Dependence of H and K emission with age of the star – From Wilson's work (1963), it is known that field main sequence F and G stars, studied at 10 Å/mm dispersion, show no more emission for stars hotter than F 5, and that 10% of the stars of type later than F 5 have an emission in H and K. For F and G main sequence stars in galactic clusters, all stars of type later than F 5 have an emission in H and K. Wilson and Woolley (1970) have studied the Ca II emission at 38 A/mm in 325 main sequence stars. The emission is found to be intense for stars whose orbit eccentricity is close to one and whose orbit inclination relative to the galactic plane is weak, hence which are the youngest in the sample. It is concluded that Ca II emission is one of the best age indicators available, being the weakest when the star is advancing in age. As a result of this age dependence H and K emission has been used as a tool to detect faint members in young clusters (Kraft and Greenstein, 1969). Because the majority of the members of the Pleiades (according to proper motion) have $K_2$ emission twice as strong as Hyades stars of the same type, the assumption was made that such an emission identifies members of the cluster even for stars fainter than V = 13. Observations have been successfully conducted at 200 A/mm for stars later than K 5 in the Pleiades. Prolongation of the main sequence toward faint members allows a determination of the contraction time of the stars in the cluster.

- Ca II emission and polarization. Dyck and Johnson (1969) have shown that the deviation of the mean degree of intrinsic polarization per night relative to the mean degree is anti-correlated to the intensity in $K_2$ for ten cool giants and supergiants. These observations have been extended to long period irregular variables by

Jennings and Dyck (1971). In those stars, H and K emission occurs only if the polarization degree is weak (0.1%), and it is exclusive with IR emission around $10\mu$. It is suggested that polarization and IR emission are due to a dust shell, the formation of which prevents a strong heating of the chromospheric gas.

- Ca II emission in binary systems. Popper (1970) mentions that 25 eclipsing systems are known with emission in H and K in the primary or in the secondary component; their types are F to K 0. The emission may undergo the eclipse. It is observed in dwarfs as well as in supergiant systems. Carlos and Popper (1971) have found the same effect in a spectroscopic binary, H D 21242, the emission being localized in the spectrum of the secondary (K 0 IV; the primary being G 5 V). Inversely, the presence of a strong $K_2$ emission in giants can be used to detect binary systems. Abt, Dukes and Weaver (1969) have studied 12 Cam (KO III) and checked that assumption with success.
- Wilson-Bappu effect. The well-known empirical relationship established by Wilson and Bappu (1957) for G, K and M stars is

$$M_v = 14.94 \log w_o + 27.59$$

where $M_v$ is the visual absolute magnitude, and $w_o$ is the width of the emission, corrected from the instrumental profile. I will not discuss this relationship and its evolutive implications here, except to mention that it has been recently extended to 200 more southern stars (Warner, 1969). The question of calibration in terms of absolute magnitudes has been critically reviewed by Wilson (1970). A possible influence of metal abundance which could perturb the general use of the relationship and was suggested by Pagel and Tomkin (1969) receives objections from Wilson in that article.

Let us recall that not all stars showing H and K emission obey the WB relationship; T Tauri do not (Kuhi, 1965); nor do Cepheids (Kraft, 1960). But the Sun does verify the WB relationship. This is why attempts to explain the luminosity effect on the $K_2$ emission width have turned first to the physical parameters of the solar chromosphere, where it is formed. Turbulence has not proved to be the key, although it was shown, originally by Jefferies and Thomas (1959), and more recently by Athay and Skumanich (1968) that the emission width, defined by Wilson, is indeed a function of the Doppler width. Recently, studies of high resolution spectrograms of the Sun have been performed, with the aim of recognizing the contribution of discrete chromospheric elements in the formation and position of the $K_2$ peaks of Ca II, by Pasachoff (1970, 1971) and by Bappu and Sivarawan (1971). By a careful study of a series of K profiles and of $K_{232}$ spectroheliograms in the quiet Sun, Bappu and Sivaraman have derived the distribution of the $K_2$ peak to peak distance on the solar surface. This width can of course be measured on spectra only when both $K_{2R}$ and $K_{2V}$ exist as bright features (about 95% of the situations). In that case, the WB relationship is satisfied. From a study of intensity fluctuations in $K_{2V}$ and $K_{2R}$ along the slit, the authors identify the emitting regions for which the WB relationship is valid with the bright fine mottles. On the other hand, it is known that the $K_2$ width decreases over plages (Smith, 1960), and at the super-granulation boundaries, where magnetic fields of the order of 100 gauss are present. Those two results suggest: (1) that in stars where the $K_2$ width obeys the WB relationship, an inhomogeneous structure like the solar mottles exists, and (2) that a deviation from WB relationship will occur in particular in stars with a magnetic activity, and will also tend to be associated with a light variation. According to Bappu and Sivaraman, the rotation of the star is a decisive parameter in modulating the rate of plages on the visible disk. At the present stage, and in spite of its interest, it is clear that this interpretation of the WB effect is somehow incomplete, in the sense that it does not offer a reason for the variation of the properties of the fine mottles with luminosity in such a way that $w_0$ is kept proportional to visual luminosity $L_v^{1/6}$.

An example of the above picture seems to exist; $\gamma$ Boo (A 7 III) is a star with a high rotational velocity (v sin(i)=135 km/s); it shows short time scale variations in the K line core. That is, it exhibits variable asymmetry, and despite the high v sin(i), the temporary occurrence of an emission (Le Contel et al., 1970). The K emission width is smaller than that expected from the WB relation, which fits Bappu and Sivaraman's suggestion if emission comes only from plages; the star is also variable in light; one of the proposed interpretations for these phenomena is that the star's surface is perturbed by plages. An extension of this scheme of interpretation to deviations from the WB relationship for Cepheids or T Tauri seems hazardous at the moment.

**IR TRIPLET OF Ca II** – The infrared lines of Ca II near to 8498 Å show no central emission in the quiet Sun. An emission core is seen over plages, the most intense being in the otherwise weakest line of the triplet, as was beautifully described by Linsky during this conference. In long period variables, like R Leo (M 8 e), Ca II triplet occurs in emission (Kraft 1957); in T Tau stars it occurs also.

**BALMER LINES OF HYDROGEN** – Because their source functions have source and sink terms dominated by photoionizations in solar type stars, these lines are comparatively insensitive to the local physical characteristics of the atmosphere, and depend mainly on the radiation field in the various continua (Thomas, 1957). The influence of a decrease of gravity is to enhance the photoelectric character of the source function. As suggested by Mihalas, the character of the Balmer lines source function changes in hot stars. Therefore, the observed emission of H$\alpha$ in hot supergiants, if not due to a geometrical effect, could be a sign, not of a chromosphere, *as previously defined,* but of a non-LTE photosphere. But H$\alpha$ in emission is not found only in hot stars. It appears in d M e stars, often simultaneously with K emission; in symbiotic stars where emission lines are superimposed on an M type spectrum; in flare stars; in T Tau stars, *etc.* (Bidelman, 1954; Herbig, 1960).

Wilson (1956) reported emission in H$\epsilon$, observed on 10 A/mm spectra of K and M type stars. Emission is first observed in K stars, and is well developed in M giants, but not in the supergiants. Excitation of the 7th level of Hydrogen by the Ca II H line does not seem likely, as $H_e$ lies too far in the wing of the H line ($\Delta\lambda$ = 1.58 Å). Ly$\eta$ could do the same, but until now it has not been observed in those stars. One wonders why only this single Balmer line (H), would be in emission through such an excitation process.

Other Balmer lines can be in emission in special groups of late type stars (symbiotic stars, Mira variables). A recent observation reports H$\gamma$ and H$\delta$ in emission in o Ceti at phases close to the maximum of light (Odell et al., 1970).

**PASCHEN LINES OF HYDROGEN** – P$\alpha$ has been predicted to be in emission in O stars under radiative equilibrium (Mihalas and Auer, 1970), but observational difficulties at that wavelength (1.8751$\mu$) have until now prevented a check of this prediction, or finding other stars where this emission could occur. But P$\beta$ (1.2818$\mu$) and P$\gamma$ (1.0938$\mu$) have been observed in emission: P$\beta$ in o Ceti (Kovar et al., 1971), and P$\gamma$ in $\gamma$ Cas (BO IV e), which is not a shell star (Meisel, 1971).

No equivalence of emission cores in Paschen or Balmer lines exists when observed over the disk in the Sun.

**HELIUM I LINE** – The triplet series lines $\lambda$10830 and $\lambda$5876, in absorption or in emission, correspond to a high excitation, and are not of photospheric origin in late type stars. $\lambda$10830 ($^3S$ - $^3P^o$) has been discovered in emission in P Cyg and in carbon Wolf-Rayet stars (Miller, 1954), then in emission in all Wolf-Rayet stars (Kuhi, 1966). Vaughan and Zirin (1968) have searched for this line in 86 stars at 8.4 A/mm and found it in absorption in normal G and K stars, and in emission in five stars, where the profile is of the P Cyg type. Meisel (1971) observed it in emission in $\gamma$ Cas. The presence of $\lambda$5876 ($^3P^o$ - $^3D$) is attributed to hot chromospheric layers in late-type stars. Wilson and Aly (1956) detected it in G and K stars, the warmer being of type G 5 V ($\kappa$ Ceti). Feast (1970*b*) found this same line in $\varphi$ Dor (F 7 V), a star which otherwise has also an intense emission in H and K. Fosbury and Pasachoff reported more observations during this conference.

In the Sun, besides the flash spectrum, λ5876 (also called D3) is observed in absorption only above active regions; λ10830 is seen in absorption over selected regions of the disk (network cells, plages and filaments)(e.g. Zirin and Howard, 1966). Both lines can be observed in emission only in bright flares. They are assumed to be formed in the strongly non-homogeneous chromosphere, namely in the hot regions, above 2000 km from the limb.

Coming now to a quite different class of objects, it has been argued by several authors (Nariai, 1969; Wickramasinghe and Strittmatter, 1970; Böhm and Cassinelli, 1971), that helium stars and white dwarfs could have a chromosphere-corona, because, according to the mixing length theory, their convection zone is predicted to be important (effect of increased He abundance or of density). Nariai gave $\nu$ Sgr as a good candidate. Observations performed on the helium star G 61-29 show broad He I emission lines, among which λ3889 has a central reversal (Burbidge and Strittmatter, 1971). No detailed interpretation of any of these He I lines in helium stars has yet been worked out, but the He I and He II spectrum in O stars is the object of an important study by Auer and Mihalas (1972). For many other lines, which might be related to chromospheres, no detailed analysis is yet available. We will only briefly mention them now.

**OTHER EMISSION LINES**

- The K I resonance doublet seems to appear definitively in emission in a small number of very peculiar stars such as the long period variable $\chi$Cyg, the peculiar supergiant VY C Ma. A single reversal is also seen in the core of this line when observed in sunspots (Maltby and Engvold, 1970).
- The O I infrared line at λ8446, observed by Wallerstein (1971) in stars showing an IR excess occurs in emission when Ca II λ3933 is broad, while it shows no emission when Ca II is sharp and in emission.
- Fe II also builds an emission spectrum in many late type stars as well as in some early types and in symbiotic stars (see e.g., Bidelman, 1954; Herbig, 1960). Can one say that their origin is chromospheric, or do they show an increase in excitation in a rather cool (relative to a chromosphere) circumstellar shell? Weymann (1962) attributes those Fe II lines observed in $\alpha$ Ori around 3100 Å to a chromo-

sphere, although in that star the Fe I excitation temperature is very low, and Fe I lines are formed in a shell. Those lines are often simultaneously present with an excess of IR in the 2-10$\mu$ range. Geisel (1970) gives a list of 35 stars, mainly hot (Be - P Cyg, Ae, Fe, Ge, and some others) where the IR excess has been predicted, and found, from the physical relationship between Fe II and [Fe III] emission and the IR excess. Such a correlation, if extended, and the already quoted exclusivity effect between Ca II K emission and polarization plus infrared excess put in full light the problem of the mutual relationship of chromospheres and dust shells around Be stars as well as around cool stars.

All the excitation anomaly indications reviewed here are lines. Moreover, all the corresponding observations concern the integrated disk of the star. In the perspective of having the Sun as a running example, we must stress that the first modern models of the solar chromosphere have been derived from the analysis of eclipse data (emission gradients in Paschen and Balmer continuum, lines of metals, Balmer lines .... see Thomas and Athay, 1961). A limited number of eclipsing systems consist of a main sequence B star and a K or M supergiant whose chromosphere is illuminated by the B star light during the eclipse. Those stars contain more information on chromospheric layers of the K or M component than any other observed only in the disk. Their prototype is $\zeta$ Aur. A review of observations and interpretations was given by Groth (1970); they will not be mentioned further here, in spite of their major interest in attacking the chromosphere problem in stars.

Besides the eclipsing systems of the $\zeta$ Aur type, several groups of stars deserve special attention relative to the observations of chromospheres. Some were incidentally mentioned: Mira variables, Wolf Rayet stars, T Tauri, helium stars, symbiotic stars. We shall add flare stars but it is not possible here to give a meaningful account of them. A recent paper on chromospheres in flare stars is that of Gershberg (1970), and a review has been given by Lovell (1971).

## IONIZATION ANOMALIES

Observations of the radio continuum have been performed, without success, on $\alpha$ Ori M 2 I ab) at $\lambda$ = 1.9 cm by Kellermann and Pauliny-Toth (1966), and with success on $\alpha$ Ori and $\pi$Aur (M 3 II) at $\lambda$ = 2.85 cm by Seaquist (1967) and on $\alpha$ Sco at $\lambda$=11.1 cm by Wade and Hjellming (1971) and Hjellming and Wade (1971). In this last case, the radioflux at 3.7 cm happens to be higher *or* smaller than the 11.1 cm flux, showing that the source is variable both in intensity and spectral index; the source seems to be associated with Antares B (B 3 V) rather than with Antares A (M 2 I b).

Coronal type lines have been observed in the spectrum of novae. The identified lines, allowed or forbidden, belong to highly ionized atoms. A bibliography can be found in the C.N.R.S. International Colloquium on novae, supernovae, novoides (1965). Recent work due to Andrillat and Houziaux (1970a, 1970b) identifies coronal lines in the near infrared region of Nova Del 1967: lines of [Fe X], [Fe XI], [A XI], [Ni XV].

Solar chromospheric temperatures have been derived from the observations of mm and cm radiation jointly with eclipse data to infer densities (e.g. Dubov, 1971). As to the coronal lines, their ionization and excitation mechanisms are fairly well understood in the Sun. But very few attempts have been made to extend the solar corona type of analysis to novae.

One of the lines having been used to characterize the properties of the transition region between the solar chromosphere and corona is the O VI doublet at 1031.9 - 1037.6 A. I don't know of any observation of this line in stars, but other O VI lines are well known in Wolf Rayet stars, and have been reported in planetary nebulae central stars and in stars which are not central (Sanduleak, 1971).

## INDICATORS OF MASS FLUX

To review all indicators of mass flux in photospheres is beyond the scope of this talk, although it would be most valuable to do so, and to examine simultaneously why some velocity fields become turbulent and others do not, and why some of them evolve until their energy is converted back to the thermal pool of the atmosphere by heating.

Let us focus our attention here only on those mass flux indicators which pertain to the chromospheric layers themselves, because these indicators are lines formed in the chromosphere. The whole question of mass *loss*, namely of net systematic escape of matter from the star, will be set aside.

## ANOMALOUS LINE-WIDTHS

A good example is that of H$\alpha$ in the solar chromosphere. This line alone cannot lead to an inference of $T_e$ in chromospheric layers. But suppose we know $T_e$ (h). To interpret the halfwidth of this line, as well as of others, a statistical broadening of the Doppler type must be added to the thermal one. This additional broadening is attributed to microturbulence.

In stars, assuming that the core of H$\alpha$ is formed in the same layers as the emission peaks of the H and K lines, Kraft et ai. (1964) studied the width of H$\alpha$ called $H_o$. They found a correlation between $H_o$ and the absolute magnitude in the U band pass. This work has been repeated by Lo Presto (1971) with improved observational facilities. He observed about ten stars with the solar tower at Kitt Peak, and obtained a better relation than Kraft's between $H_0$ and $M_V$. This result extends in fact to $H_\alpha$ the Wilson-Bappu relationship, without, nevertheless, reinforcing an interpretation of this relationship in terms of solely a turbulence effect. Further work is in progress on late-type stars of all luminosity classes (Fosbury, 1971).

No exceptions have been reported (to my knowledge) to the empirical relationship between $H_0$ and $M_v$ and so there is no counterpart on $H_q$ to T Tau or Cepheids disobeying the WB relationship.

According to Vaughan and Zirin (1968), the He I λ10830 line seems also to show a broader profile than photospheric lines in stars where it has been observed.

The same is true (enhanced line-width, from which astronomical turbulence is invoked) for Wolf-Rayet stars emission lines, certain of which show a P Cyg profile, and hence reflect that the emitting region experiences mass ejection.

## ASYMMETRICAL LINES

Both Ca II and Mg II resonance doublets are strongly asymmetric in the quiet Sun (e.g. Pasachoff, 1970; Bappu and Sivaraman, 1971; Lemaire, 1971). For Ca II, a statistical analysis has been performed by Bappu and Sivaraman on the occurrence of different patterns for the relative $K_{2V}$ and $K_{2R}$ intensities: $I_{K_{2V}}$ is bigger than $I_{K_{2R}}$ in 45% of the profiles; they are equal in 4.7%; $I_{K_{2V}}$ is smaller than $I_{K_{2R}}$ in 25%; $I_{K_{2R}} = 0$ in 22.3%; $I_{K_{2V}} = 0$ in 0.7% of the cases.

In stars, the profiles of Ca II K line obtained by Liller (1968) or by Vaughan and Skumanich (1970), even if they show only one central emission core, are very far from being symmetric. The core of Hα is also often asymmetric in late type stars (see Kraft et al., 1964; Weymann, 1962). Some of the HeI λ10830 profiles observed by Vaughan and Zirin in hot stars exhibit a P Cyg type profile. The chromospheric layers are then associated with directed velocity fields indicating mass transport towards the interstellar medium.

## INDICATORS OF HORIZONTAL INHOMOGENEITIES AND OF ACTIVITY

In the Sun, Doppler shifts and intensity fluctuations along the slit in lines allow study of both the propagation of waves and the solar fine structure in the upper photosphere and low chromosphere. On the other hand, on spectroheliograms and filtergrams, one sees the coarse network, coarse mottles and fine mottles, as well as spots, filaments and other features, and inhomogeneities prove to extend high up in the chromosphere. In stars, no such observations can be performed, except possibly in eclipsing systems of the $\zeta$ Aur type. We will then restrict ourselves here to indicators of temporal variations in stellar chromospheric spectra, ignoring spacial inhomogeneities.

Variations have been observed in H and K lines and for stars where these lines happen to show central emission. Several other chromospheric lines undergo variations also.

*In H and K,* these variations affect the intensity of the emission peaks and the shape of the profile. Let us consider first late-type stars. Griffin (1963) and Deutsch (1967) first reported such variations in $\alpha$ Boo and other cool giants. Variations in the K emission can be occasional (e.g. Kandel, 1966, in the dwarf HD 119850; Boesgaard, 1969, variations in the MS star 4 Ori). Although they have been searched for, to the best of my knowledge, no cyclic variations in the K line flux have yet been reported (Wilson, 1968; Liller, 1968). This might only reflect the lack of long enough time sequences of observations.

If these variations are associated with changes in the physical properties of the emitting atmosphere (occurrence of plages, for instance), one wonders if this activity is correlated with a general brightness variation of the star. Such photometric variations have been searched in the UBV filters by Blanco and Catalano (1970), on HD 119850 ( d M 2.5 e), $\alpha$ Boo (K 1 III) and $\alpha$ Tau (K 5 III). No clear variations can be detected. Similar observations were made by Krzeminski (1969) on a sample of d Me and d M stars. Light variations exist in some d M e stars, showing that activity is a continuous process; but none are present in d M. The extreme example of stars showing activity in light as well as in chromospheric lines (H$\alpha$ core, Ca II) is that of flare stars, also classified as UV Ceti variables.

Among variables with chromospheric characteristics, Mira stars also prove to be variable in their emission lines; e.g., variation in H $\gamma$, H $\delta$ reported by Odell et al., (1970), variation in P$\beta$ reported by Kovar et al., (1971).

Toward hotter stars, the already mentioned A 7 III star, $\gamma$ Boo, shows a quasi-periodic velocity field from radial velocity measurements at mid-intensity in the K line, and a variable K line reversal within time intervals of 2 hours (Le Contel et al., 1970). Due to lack of observations, no period has been recognized for the K line core variation; hence, it has not been related to the light variation which the star experiences with a period of 0.29 d. The light amplitude is variable, and phases of calm with no variations at all do exist.

In *Of stars,* which have not been considered in detail in this paper, variations in strengths of the emission lines N III $\lambda$4034, 4640, 4641 and He II 4686 have been observed by Brucato (1971) with a time scale of the order of ten minutes. A typical *Of stars,* $\zeta$ Pup, is also one of the stars which ejects mass at the highest known velocity (Carruthers, 1968).

The *HeI line* $\lambda 10830$ experiences variation, as in the Sun (Vaughan and Zirin, 1968), in several late type stars.

A puzzling case appears to be that of the star *R Cr B*, whose chromospheric properties have been pointed out by Feast (1970), after Payne-Gaposhkin (1963) and others. The H and K cores, D lines of Na I and sharp Sc II, Ti II, Sr II, and Fe II lines appear in emission when the star (F 7 carbon supergiant and irregular variable) goes through the minimum of light. That phase has been suggested to coincide with the ejection of condensed graphite which obscures the star. If this is the case, it seems difficult to reconcile the presence of this carbon black cloud with that of a chromosphere, namely a heated layer, because to have carbon change phase, one most likely requires heat absorption instead of dissipation. On the other hand, during phases of maximum light, and over one year, R Cr B has been variable in the infrared continuum (Forrest et al., 1971) at $3.5\mu$, while at $11.1\mu$ it was quasi-stable. The variation amounts to 1.5 mag, which means that the circumstellar carbon grains have been heated, whatever the form of energy input. We may assent to a possible alternation between absorption of heat to produce grains, and heating of those grains.

## CONCLUSION

Obviously, an enormous gap exists between observations as they stand, on the one hand, and their interpretation in terms of the general structure of a stellar atmosphere, on the other hand.

There is no such thing as an available grid of stellar chromospheric models (although stellar coronas have been quantitatively predicted). One has to realize, case by case, for each interesting star, that the observational information is scarce enough so that one has difficulties applying a solar analogical method, such as described by Avrett, to analyze them. Attempts were made by Kandel (1967) and by Simon (1970) to produce chromospheric models for d M stars, in one case, and for Arcturus ($\alpha$Boo), in the other.

At the moment, we have not fulfilled the scheme for analysis which the introduction claimed to be legitimate in looking at stellar chromospheric indicators. This may mean that we have not given the *useful* definition of a chromosphere required at the beginning of the conference. We have been able to classify many of these indicators by referring them to heating or to mass flux. But we have met at least three important problems on which we have had to be vague. One is diagnostical, and has been outlined by Jefferies. Are all emission lines a signature for a chromosphere? The second is structural. How could we specify the base of the chromosphere at all, and how do we do this when a circumstellar shell is related to it, especially in stars where the shell seems to be very close to the photospheric layers? The third question relates to the physics of velocity fields. Do all motions detected in photospheres become turbulent and are they a result of atmospheric heating? If not, what are they like and what causes them?

A way to progress is surely to call for more observations, but for more systematic ones, in the sense that we want them to be led as closely as possible by a physical question to answer. The most immediate step to take would be to collect, from a limited number of objects, information from all spectral regions, lines and continua, to be able to construct reliable spherically symmetrical models of $T_e(h)$, those models being obtained using the static energy balance equation, taking into account line effects, and treating the mechanical energy input as a free parameter, if no better treatment is possible. A simultaneous effort should be pursued to answer the precedingly quoted questions, whose answers will influence the construction of a model.

This paper was prepared partly when I was in JILA, as a Visiting Fellow (1970-1971); I have benefitted from numerous clarifying discussions there, as well as in France, and I acknowledge especially the continuous interest of Ph. Delache, J. – C. Pecker, R Steinitz, and R.N. Thomas. I am also indebted to all colleagues who sent me preprints of their current work before the Goddard Conference.

## REFERENCES

Abt, H.A., Dukes, R.J., Weaver, W.B., 1969, Ap. J. **157**, 717
Andrillat, Y., Houziaux, L., 1970, Astrophys. Space Sc. **6**, 36
Andrillat, Y., Houziaux, L., 1970, Astrophys. Space Sc. **9**, 410
Athay, R.G., Skumanich, A., 1968, Ap. J. **152**, 141
Athay, R.G., 1970, Ap. J. **161**, 713
Auer, L.H., Mihalas, D., 1969, Ap. J. **156**, 157, 681
——————1970, Ap. J. **160**, 233
——————1972, Ap. J. Suppl. **24**, 193
Bappu, M.K.V., Sivaraman, K.R., 1971, Sol. Phys. **17**, 316
Bidelman, W.P., 1954, Ap. J. Suppl. **1**, 175
Blanco, C., Catalano, S., 1970, PASP **82**, 2293
Boesgaard, A.M., 1969, PASP **81**, 283
Böhm, K.H., Cassinelli, J., 1971, Astr. Astrophys., **12**, 21
Brucato, R.J. 1971, MNRAS **153**, 435
Burbidge, E.M., Strittmatter, P.A., 1971, Ap. J. **170**, 139
Carlos, R.C., Popper, D.M., 1971, PASP **83**, 504
Carruthers, G.R., I 1968, Ap. J. **151**, 269
Cayrel, R., 1963, C.R. Ac. Sci. **257**, 3309
Coll. Int. C.N.R.S., 1965 Novae, Novoides et Supernovae, Ed. C.N.R.S., Paris
Deutsch, A.J., 1967, PASP **79**, 431
Dubov, E.E., 1971, Solar Phys. **18**, 43
Dyck, H.M., Johnson, H.R., 1969, Ap. J. **156**, 389

Feast, M.W., b 1970, MNRAS **148**, 489
a 1970, in Ultraviolet Stellar Spectra and Ground Based Observations, Ed. L. Houziaux, H.E. Butler, p. 187
Feautrier, P., 1968, Ann. Astr., **31**, 257
Forrest, W.J., Gillett, F.C., 1971, Ap. J. **170**, L 29
Fosbury, R.A.E., 1971, private communication
Frisch, H., 1966, JQSRT **6**, 629
Gebbie, K.B. Thomas, R.N., 1971, Ap. J. **168**, 461
Geisel, S.L., 1970, Ap. J. **161**, L 105
Gershberg, R.E., 1970, Astrofizika **6**, 191
Griffin, R.F., 1963, Observatory **83**, 255
Groth, H.G., 1970, in Spectrum Formation in Stars with Steady-State Extended Atmospheres, Ed. H.G. Groth, P. Wellmann, NBS Spec. Publ. 332, p. 283
Herbig, G.H., 1960, Ap. J. Suppl. **4**, 337
Hjellming, R.M., Wade, C.M., 1971, Ap. J. **168**, L 115
Jefferies, J.T., Thomas, R.N., 1959, Ap. J. **129**, 401
Jennings, M.C., Dyck, H.M., 1971, K.P.N.O. Contr., **554**, 203
Kandel, R.S., 1966, in Coll. on Late Type Stars, Trieste, Ed. M. Hack, p. 146
Kandel, R.S. 1967, Ann. Astr. **30**, 999
Kellermann, K.I., Pauliny-Toth, I.I.K., 1966, Ap. J. **145**, 953
Kovar, R.P., Potter, A.E., Kovar, N.S., 1971, BAAS **3**, 351
Kraft, R.P., 1960, in Stellar Atmospheres, Ed. J.L. Greenstein, Chicago Univ. Press, p. 401
Kraft, R.P., Preston, G.W. Wolff, S.C., 1964, Ap. J. **140**, 235
Kraft, R.P., Greenstein, J.L., 1969, in Low Luminosity Stars, Ed. S.S. Kumar, p. 65
Kraft, R.P., 1957, Ap. J. **125**, 326
Krzeminski, W., 1969, in Low Luminosity Stars, Ed. S.S. Kumar, p. 57
Kuhi, L.V., 1965, PASP **77**, 253
————1966, Ap. J. **145**, 715
Lecontel, J.M., Praderie, F., Bijaoui, A., Dantel, M., Sareyan, J.P., 1970, Astron. Astrophys. **8**, 159
Lemaire, P. 1971, Thesis, University of Paris
Liller, W., 1968, Ap. J. **151**, 589
Lo Presto, J.C., 1971, PASP **83**, 674
Lovell, B., 1971, QJRAS **12**, 98
Maltby P., Engvold, O., 1970, Solar Phys. **14**, 129
Meisel, D.D., 1971, PASP **83**, 49
Mihalas, D., Auer, L.H., 1970, Ap. J. **160**, 1161
Miller, F.D., 1954, A.J. **58**, 222
Nariai, K., 1969, Astrophys. Space Sc. **3**, 160
Odell, A.P., Vrba, F.J., Fix, J.D., Neff, J.S. 1970, PASP **82**, 883
Pagel, B.E.J., Tomkin, J. 1969, QJRAS **10**, 194
Payne-Gaposhkin, C., 1963, Ap. J. **118**, 320
Pasachoff, J.M., 1970, Solar Phys **12**, 202

Pasachoff, J.M., 1971, Ap. J. **164**, 385
Popper, D.M., 1970, in Mass Loss and Evolution in Close Binaries, Ed. K. Glydenkerne and R.M. West (Copenhagen: Univ. Publ. Fund) p. 13
Praderie, F., 1970, in Spectrum Formation in Stars with Steady-State Extended Atmospheres, Ed. H.G. Groth, P. Wellman, NBS Special Publ. 332, p. 241
Sanduleak, N., 1971, Ap. J. **164**, L 71
Seaquist, E.R., 1967, Ap. J. **148**, 123
Simon, T., 1970, Thesis, Harvard.
Skumanich, A., 1972, Ap. J. **171**, 565
Smith, E. van P., 1960, Ap. j. **132**, 202
Thomas, R.N. 1957, Ap. J. **125**, 260
Thomas, R.N., Athay, R.G., 1961, Physics of the Solar Chromosphere, Inter-Science Publ.
Vaughan, A.H., Zirin, H., 1968, Ap. J. **152**, 123
Vaughan, A.H., Skumanich, A., 1970, in Spectrum Formation in Stars with Steady-State Extended Atmosphere, Ed. H.G. Groth, P. Wellman, NBS Spec. Publ. 332 p. 295
Wade, C.M. Hjellming, R.M., 1971, Ap. J. **163**, L 105
Wallerstein, G., 1971, PASP **83**, 77
Warner, B., 1969, MNRAS **144**, 333
Wesson, P.S., Fosbury, R.A.E., 1972, Observatory (in press)
Weymann, R., 1962, Ap. J. **136**, 844
Wickramasinghe, D.T., Strittmatter, P.A., 1970, MNRAS **150**, 435
Wilson, O.C., 1954, Conference on Stellar Atmospheres, Indiana Univ., Proc. Nat. Sc. Foundation, Ed. M.H. Wrubel, p. 147
Wilson, O.C., 1956, Ap. J. **126**, 46
Wilson, O.C., Aly, M.K., 1956, PASP **68**, 149
Wilson, O.C., Bappu, M.K.V., 1957, Ap. J. **125**, 661
Wilson, O.C., Skumanich, A., 1964, Ap. J. **140**, 1401
Wilson, O.C., 1962, Ap. J. **136**, 793
Wilson, O.C., 1963, Ap. J. **138**, 832
Wilson, O.C., 1966, Ap. J. **144**, 695
Wilson, O.C., 1968, Ap. J. **153**, 221
Wilson, O.C., 1970, Ap. J. **160**, 225
Wilson, O.C., 1970, PASP **82**, 865
Wilson, O.C., R. Woolley, 1970, MNRAS **148**, 463
Zirin, H., Howard, R., 1966, Ap. J. **146**, 367